

High-Frequency Acoustics of Ocean Sediments and Biot's Theory

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Grant #: N00014-98-1-0062
<http://www.arlut.utexas.edu>

LONG-TERM GOALS

A physical model of high-frequency sound interaction with the seafloor including, penetration through the water-seafloor interface, as well as propagation within and scattering from the seafloor, in support of ASW and MCM applications.

OBJECTIVES

Using results of the SAX99 experiment and additional laboratory measurements in the ARL:UT sand tank, a new and improved model of sediment acoustics was developed that is consistent with all known values of geophysical parameters and acoustic measurements.

APPROACH

There were two parallel approaches to the problem. The first approach used data from the SAX99 experiment to guide the model development effort. The analysis was by Nicholas Chotiros, ARL:UT, with supporting data from numerous SAX99 participants including Eric Thorsos and the APL/UW team, Michael Richardson and the NRL team, Anthony Lyons and the SACLANTCEN team and others. The SAX99 data set was very comprehensive but there was significant surface roughness that could mask the intrinsic acoustic properties of the sediment. The second approach used a flat sand surface in a laboratory tank to avoid the roughness problem entirely, and employed inversion of reflection loss as a function of angle and frequency - measurements which were not taken at SAX99. The effort was lead by Marcia Isakson, ARL:UT. The two approaches are very complementary. A number of candidate models were tested. The candidate models were tested for their ability to match experimentally measured acoustic properties, including reflection loss, and wave speeds and attenuations, and known or measured geophysical properties, such as density, porosity, elastic moduli and flow properties.

Report Documentation Page			Form Approved OMB No. 0704-0188		
Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.					
1. REPORT DATE 30 SEP 2002		2. REPORT TYPE		3. DATES COVERED 00-00-2002 to 00-00-2002	
4. TITLE AND SUBTITLE High-Frequency Acoustics of Ocean Sediments and Biot's Theory				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S)				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Applied Research Laboratories,,The University of Texas at Austin,,Austin,,TX, 78713				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT A physical model of high-frequency sound interaction with the seafloor including, penetration through the water-seafloor interface, as well as propagation within and scattering from the seafloor, in support of ASW and MCM applications.					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT Same as Report (SAR)	18. NUMBER OF PAGES 6	19a. NAME OF RESPONSIBLE PERSON
a. REPORT unclassified	b. ABSTRACT unclassified	c. THIS PAGE unclassified			

WORK COMPLETED

In the laboratory sand tank at ARL:UT, the reflection coefficient was measured over a flat water-sand interface, over a range of frequencies (30-150 kHz) and grazing angles (7-66 degrees) and at normal incidence. The data were compared to five different models: the visco-elastic model, the effective density model of Williams [1], Buckingham's model [2], the Biot-Stoll poro-elastic model [3] and its extensions [4]. The data were inverted using a simulated annealing inversion algorithm developed under the Environmentally Adaptive Shallow Water Signal Processing project. OASES was used as the forward model. The inversion results were used for model development.

The same set of candidate models were tested against the SAX99 data set. In this case, the acoustic data consisted of reflection loss at normal incidence and in-situ wave speed and attenuation measurements. The normal incidence reflection loss was corrected for the effects of interface roughness. The data were inverted using an iterative process. Some of the results were published in The Journal of the Marine Acoustics Society of Japan and presented at the Underwater Technology conference 2002 in Tokyo. Furthermore, work on a broad-band extension of the sediment acoustic model was initiated, using the unique dispersion and attenuation measurements by SAX99 participants.

RESULTS

The discrepancy between visco-elastic models and the acoustic response of sandy sediments was clearly demonstrated and the main causes were revealed. Visco-elastic and fluid-fluid models, including Buckingham's model, required a lower value for sediment density than the true value to match measured values of reflection loss. This is because these models have no mechanism for accounting for the relative motion between the sediment grains and the pore fluid. The Biot-Stoll poro-elastic model, including the effective density model of Williams, has the necessary physics to account for the relative motion and properly model the effective inertial effects.

The Biot-Stoll model, including the effective density model of Williams, were a big improvement over visco-elastic and fluid-fluid models, but they were inconsistent with measurements with regard to the value of the grain bulk modulus. The inverted value was significantly higher than the recently measured value for quartz sand by Briggs et al. [7].

The composite Biot-Stoll model as formulated by Chotiros[4] overcame this inconsistency and produced realistic values for all parameters that agreed with experimental measurements. This is the first time that a sediment acoustic model has successfully matched all measurable geophysical parameter values and acoustic properties for sandy sediments.

Using the inversion results, it was found that the poro-elastic model predicted an increase in the influence of wave-front curvature at shallow grazing angles, which had the effect of delaying the arrival of the pulse relative to a visco-elastic or fluid model. This effect should be evident in transmission measurements and will serve as further verification of the theory.

Within the context of the composite Biot-Stoll model, the inversion results for the laboratory sand were quite different from those of SAX99. For the laboratory sand, the inverted slow wave speed was very low, signifying that the slow wave effects were insignificant. The inversion indicated that the relatively high reflection loss at very shallow grazing angles was caused by the attenuation of the

sediment sound wave. The inverted values of frame fluid fraction and solid fraction of fluid, though quite small, enabled the model to fit all of the known parameter values and acoustic measurements. For the SAX99 data, the inverted slow wave speed was much higher, indicating significant slow wave effects. The solid fraction of the fluid was also quite high indicating that a large fraction of the grains were disconnected from the skeletal frame and suspended in the fluid. This may be due to biological activity in the sediment. These results indicate that the acoustic response of sands may vary significantly depending on environmental factors.

IMPACT/APPLICATIONS

For the first time, a model has been formulated that is physically sound and capable of matching all measurable geophysical parameters and acoustic properties, including wave speeds and attenuations of water-saturated sand and the reflection loss at the water-sand interface. All of the current standard acoustic propagation and scattering models that have been accepted and certified by the Navy's Ocean Acoustic Mathematical Library (OAML) approximate the ocean sediment as a visco-elastic medium. This study has identified the deficiencies of the visco-elastic approximation and an improved model has been developed. Significant values of reflection loss at shallow grazing angles will also have an impact on long-range propagation modeling in ASW applications, particularly in littoral waters where long range propagation loss is largely controlled by bottom reflection loss.

TRANSITIONS

The results provided a theoretical framework for analyzing bottom reverberation data currently being collected by NAVOCEANO, and sonar performance predictions sponsored by ONR code 322 under contract N00039-96-D-0051-1-102-1.

RELATED PROJECTS

This project is tightly coupled to the other projects under the ONR "High-Frequency Sediment Acoustics" DRI, since the environmental inputs required for analysis are dependent on other projects within the DRI, and to parallel experiments conducted by the Naval Research Laboratory (NRL). The project has benefited from data exchanges with the Acoustic Penetration Experiment (APEX) of the SACLANTCEN, in Italy, on a similar sandy sediment in the Mediterranean. Laboratory studies by the LMA, under the sponsorship of the Groupe d'Etude Sous-Marine d'Atlantique (GESMA), France, are producing complementary measurements, and GESMA has expressed an interest in having similar sediment penetration measurements made on the French coast. The simulated annealing inversion for reflection that was developed for the laboratory experiment is being applied to ambient noise inversions for the Environmentally Adaptive Shallow Water Signal Processing project. This inversion will determine environmental parameters more accurately to aid in locating and identifying shallow water targets. This study is closely connected with the electro-kinetic study being conducted here at ARL:UT, which may illuminate some of the model shortfalls by isolating the fast and slow Biot waves.

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